Robotic fibre placement process planning and control

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ABSTRACT

Composite materials are being used extensively in many industry sectors. These materials are generally lightweight and offer attractive strength-to-weight and stiffness-to-weight ratios over the traditional structural materials (e.g. steel, aluminium and wood), thus suitable for many applications in the aerospace and automotive industries. However, the traditional methods of producing composite components involve hand lay-up and tape laying. Not only are these approaches time-consuming, labor intensive and hazardous, but also the material scrap rate is high and efficiency is limited. The operator must have a thorough understanding of the materials he or she is using. The thermoset tape can cause serious injury if stringent safety precautions are not maintained. Furthermore, the operator must understand that the highest quality in craftsmanship should be practiced since the process of hand lay-up is not repetitive. Defects, especially within the aerospace industry, can contribute to the loss of life. Manufacturers are demanding faster and more cost effective production processes, therefore robotic fibre placement may be introduced to overcome some of the problems. Further, robotic fibre placement can also provide benefits through cost and time reduction as reported by other researchers.

FULL TEXT

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Introduction

Composite materials are being used extensively in many industry sectors. These materials are generally lightweight and offer attractive strength-to-weight and stiffness-to-weight ratios over the traditional structural materials (e.g. steel, aluminium and wood), thus suitable for many applications in the aerospace and automotive industries. However, the traditional methods of producing composite components involve hand lay-up and tape laying. Not only are these approaches time-consuming, labour intensive and hazardous, but also the material scrap rate is high and efficiency is limited. The operator must have a thorough understanding of the materials he or she is using. The thermoset tape can cause serious injury if stringent safety precautions are not maintained. Furthermore, the operator must understand that the highest quality in craftsmanship should be practiced since the process of hand lay-up is not repetitive. Defects, especially within the aerospace industry, can contribute to the loss of life (Groppe, 2000). Manufacturers are demanding faster and more cost effective production processes, therefore robotic fibre placement may be introduced to overcome some of the problems. Further, robotic fibre placement can also provide benefits through cost and time reduction as reported by other researchers (Meason and Sewell, 1996; Tessnow et al., 1994).

Robotic fibre placement is an extension on the filament winding technique. It uses a fibre-processing head in conjunction with a robot manipulator to form parts using pre-impregnated composite fibre tows. The use of a manipulator increases the flexibility of the manufacturing process and allows the production of more complex parts, which are not attainable with other production techniques. In addition, robotic fibre placement offers other important features and advantages that are not achieved with hand lay-up and filament winding. These features are debulking of material in-situ, cutting and restarting of the tows on the fly and precise control of fibre placement in different angles. These advantages lead to a wider range of applications and higher level of performance.

While many different types of composites exist, the most mature and promising materials for inertia-loaded structures are those based on carbon fibre reinforced polymers (Ahrens et al., 1998). Fibres are the load-carrying members in composite materials and the surrounding matrix helps to position and transfer load between the fibres. Therefore, different volume ratios of fibre and matrix will give different stiffness to the composite materials. However, the challenge in robotic fibre placement involves the need to orientate the continuous fibre in multiple directions to give a desired strength. The only drawback to this new technology is the high capital cost of equipment and thus utilisation has been limited to large organizations. One other reason for the high cost is the requirement to refrigerate the thermoset prepreg tows to prevent premature curing.

2. Experimental setup

Plates 1 and 2 shows the setup of the robotic fibre placement system. The prepreg tows that are stored in a creel system are fed through a series of precision guiding chutes of the fibre-processing head manually after the tows have naturally reached room temperature. Prepreg tows are fibres pre-impregnated with a controlled amount of thermoset resin and then partially cured to give it tack quality.

The fibre-processing head is attached to the robot's end-effector. Two main components of the fibre-processing head are the vortex cooling tube and the hot nitrogen gas torch. Both temperatures can be set and controlled. When the tows enter the fibre-processing head, they will be cooled continuously by the vortex cooling to about 10[degrees]C to reduce the tackiness of the tows, so that they will not stick to the guide chute during fibre placement process. The tows will then be guided by a series of rollers into the guide chute before being heated and compacted onto the surface. The hot gas torch will apply heat to the tows to increase the tackiness of the tows. Nitrogen gas is used to heat the tows to prevent oxidative degradation during the bonding process (Moddeman et al., 1986; Day et al., 1989a, 1989b). A compaction roller will then apply direct contact between the tows and the substrate material to make sure that the tows are bonded to the surface and to remove trapped air or spatial gaps (voids). In this way, the viscosity of the matrix resin is reduced and the materials are bonded together, both tacking and debulking the materials in the process (Pasanen et al. (n.d.)). Proper compaction is therefore necessary to prevent residual stresses, voids and warping. During the fibre placement process, the robot's end-effector must be orientated in such a way that the compaction roller pressure always acts normal to the surface. Figure 1 shows the schematic diagram of the fibre placement head assembly.

To continue laying the fibres in a different direction, the tows have to be cut. The robot manipulator is then moved to the desired starting position and the tows will be fed by a servo motor. The whole process will then be repeated again. After the part has been produced, it has to be cured in an autoclave-processing oven where heat and pressure are applied to the laminate. Figure 2 shows the different stages for fibre placement from installation of hardware to quality control and testing of the end products.

3. Simulation and planning for robotic fibre

Traditionally, the programming of an industrial robot has used the "teach-mode" method, where the robot is jogged to the desired positions point by point using a teach pendant. At each different point, the position is recorded. Once the teaching is complete for a particular task, the robot controller is used in a playback mode to test the program. This approach can be very time-consuming and tedious. Furthermore, errors in task planning can be very costly. This may cause the robot to collide with a fixture or another device in the working environment. A different approach may be used for robot motion planning and programming in robotic fibre placement process. This method uses CAD models of the robot and other fixtures within a simulation environment rather than the actual hardware, to perform the task planning and the robot programming in an off-line manner.

3.1 Off-line programming of robotic fibre placement operation

Off-line programming is a teaching method that allows the operation to be planned, simulated and application programs are created on a remote computer using CAD based software. It also allows the user to plan robot manipulation strategies and perform the simulation without the need for access to the robot or other devices in the workspace (Hornick and Ravani, 1986; Quinet, 1995).

Figure 3 shows the flowchart of the off-line programming operation for robotic fibre placement process. The workcell layout is designed to specify the positions for the robot and other devices. The models drawn, using a CAD based software program called Envision, must contain the same dimensions as the actual devices. After the model development stage, programming of the robot to perform specific tasks will then be carried out. This will include fibre path generation to be described later. Once the programming stage is completed, simulation may be conducted to verify the process. During the simulation, errors might occur due to programming errors, collision between the robot and other devices, as well as encountering unreachable points. Modifications to the original program must be made to correct these errors. The program is then downloaded to the robot controller in its native language to perform the task.

3.2 Online process control

This is the stage when the actual fibre placement process is performed using the robot and other hardware. Although the simulation in off-line programming provides a very good starting point for the fibre placement process, various parameters still need to be specified online. This is because the strength of the bonding between the tows and the substrate is dependent upon the specific thermodynamic and mechanical condition under which the consolidation takes place (Mondo and Parfrey, n.d.; Hauber and Cirino, 1993). Therefore, optimization of the process involves careful selection of different parameters. These parameters include the hot gas torch temperature, raw material used, compaction force, tool temperature and material feed rate.

4. Fibre path generation

This is an integral part of formulating the development software for fibre placement process. The quality of the end product is largely dependent on how the original fibre path is generated. This is a process in which tag points (i.e. coordinate frames for position and orientation of the fibre placement head) are generated automatically on the selected part on which the tows are to be placed (Shirinzadeh and Tan, 1999). Generally, there are two different algorithms for parts made on a flat platform and on a mandrel for axis-symmetric parts.

4.1 Path generation for open surfaces

Placement of tag points with appropriate orientation on the surface can be obtained using a built-in library function in the simulation software program. However, this function does not place the tags evenly along the surface in the x and y directions. This would result in the undesirable effect of having gaps between adjacent tows. In addition, this approach does not form any useful paths. It only places tag points on the selected surface. The robot will not recognize which tag point to go to first if there is no existing path. For these reasons, a recursive numerical algorithm for the creation of paths on an arbitrary B-spline surface was developed.

Figure 4 shows the schematic diagram of a part with tag points generated on its surface and Figure 5 details the recursive numerical algorithm. As the tow width is known, to place a tow along the edge (assuming that each tag represents the centre of the tow when it is laid down), it is necessary to form a path with a distance of half the tow width from the edge. This is achieved by taking a weighted average of the position and orientation of two tag points surrounding the distance (tow width/2) along k-axis, i.e. tags T[sub]j,k and T[sub]j,k+1. For instance, if the tow width is 40mm, then a path should be placed 20mm from the edge of the part. At this stage, we do not know the position or orientation of the new tag. However, we do know that the tag should be placed in between the original tags T[sub]j,k and T[sub]j,k+1. If the distance between these two tags is 70mm, then the new tag should be located closer to tag T[sub]j,k. The orientation of the new tag, T[sub]j,k[sup]' should look similar to tag T[sub]j,k. Hence, a straight line approximation is assumed between T[sub]j,k and T[sub]j,k+1, and the weighted average of the position and orientation of the new tag point with respect to T[sub]j,k is found in this case to be 2/7 (20mm/70mm) of T[sub]j,k. This process is replicated with the next two tags T[sub]j+1,k and T[sub]j+1,k+1, then T[sub]j+2,k and T[sub]j+2,k+1 and all the way up the edge of the part as shown by the dotted line in Figure 4.

The next path should be parallel to the new tags just created. This time a new distance is created that is a further tow width away from the previous path. This is then repeated along the j-axis and all the way up the part again with the same new distance. The process is repeated along the k-axis until tag points have been generated for the whole surface. Finally, the tags that are not on the surface of the part are deleted. Figure 6 shows the tag point distribution on a complex open surface. Obviously, increasing the resolution (i.e. placing more tag points on the surface of the part) will create more accurate paths for the robot to follow, thus resulting in a better fibre placement process. Although increases in resolution will increase the computing time as well, this is not of great concern as the task is to be completed off-line. For rectangular, flat surfaces, the placement of tags will be straightforward since this does not involve the changing of orientation of the tag points. The only concern would be the tow width and the angle at which the tows are placed.

4.2 Path generation for closed surfaces

An algorithm was also developed for placing or winding fibres on an axis-symmetric mandrel. Axis-symmetric refers to a surface of revolution - a surface that is generated by revolving it around a specific axis. Examples of such structures are simple cylinders and spheres. The algorithm is based on the determination of the optimum angle of winding, the optimum number of circuits, and the optimum speed required to achieve complete coverage. Figure 7 shows the variables for the tow placement on a constant cylindrical shape with diameter D. The lead of a cylinder is defined as the linear movement per revolution.(see equation 1)where [alpha] represents the winding angle.

During the fibre placement process, the robot will be moving at a constant speed across the mandrel length. Therefore, the number of circuits required for complete coverage can be determined using the following equations:

(see equation 2)(see equation 3)where BW' is the effective band width as shown in Figure 6, BW is the band width and N represents the number of circuits for complete coverage. The band width is dependent on the tow width and the total number of tows that are being fed. Once the optimum number of circuits are calculated, the algorithm produces the head angle change that occurs just before the last tag point is reached on the forward cycle. The head angle must be adjusted in order to avoid repetition of the fibre placement pattern as the mandrel rotates. The concept of lead factor was used to calculate the head angle adjustment. Lead factor approximation is dependent on how close the tag points are on the mandrel surface. This implies that the more tag points there are, the closer the approximation is of the fibre path generated. The fomulation is illustrated as below:(see equation 4)(see equation 5)(see equation 6)where X_Length is the horizontal incremental length along the mandrel surface where the tag points are placed. [alpha][sub]i can be determined using equations (2) and (3) in terms of number of circuits, N. The adjusted lead factor, LF' can be computed by the formula:(see equation 7)Hence, by equating equations (6) and (7), the adjusted winding angle can be calculated:

(see equation 8)Figure 8 shows the tag point distribution on an axis-symmetric closed surface and Figure 9 shows the fibre placement process simulation.

5. Control system architecture

The control system architecture for robotic fibre placement process is called a SCADA (supervisory control and data acquisition) system (Harris et al., 1998). After the simulation is successfully performed on a remote computer, the program is then downloaded via LAN (local area network) onto the host computer. The host computer then compiles the turbo link program and prepares it for use within the application program. Within this application program, data acquisition as well as robot and process control can be achieved in real time. This is achieved by utilizing a turbo link card and an RS-232C serial connection. In this approach, the data points (sometimes exceeding 60,000 points) are stored in host computer's memory instead of the memory of the MRC controller. The point-to-point execution through the serial link provides almost no limit on the amount of data points used. This approach also allows online process control based on sensor data (e.g. force/torque sensor). The use of the teach pendant is also eliminated.

In addition, the MRC controller is also able to control the various operations of the fibre head (e.g. cutting of tows, tow feeding, engaging pinch roller, etc.). This is achieved by a direct connection for the various I/O signals between the fibre head controller and the MRC controller. The hot gas torch temperature, vortex cooling temperature, compaction force and the nitrogen flow must be preset on the fibre head controller before the process is performed. However, these parameters can be changed in real-time.

6. Future work

The mandrel has been designed and is currently under development. Although fibre placement on open surfaces can be successfully carried out, procedure for optimisation of the process has yet to be developed. This involves investigation of dominant process parameters (i.e. hot gas temperature, compaction force and feed rate). Testing and analysis (for example, material test, ballistic test and static test) for post process quality checking needs to be formulated.

Furthermore, online monitoring of the process using an infrared imaging system may also be implemented later. This enables the user to check on a computer screen for any defect during the fibre placement process. For example, if a crack or a gap is detected, the process will be halted and the part will be repaired in-situ.

7. Conclusion

Robotic fibre placement allows automated fabrication of complex structures that are not met previously using hand lay-up or filament winding. This new method provides faster and better repeatability of fabrication, thus increasing the quality of the products and decreasing the production cost. Off-line programming was implemented to design the workcell, plan and simulate the fibre placement process before the actual fabrication process is performed online. Programs have also been written to generate fibre path for both open and closed surfaces.

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Illustration

Caption: Plate 1; Setup of robotic fibre placement process; Plate 2; Close up of the fibre placement head; Figure 1; Schematic diagram of the fibre placement head assembly; Figure 2; Different stages of the robotic fibre placement process; Figure 3; Algorithm for off-line programming of robotic fibre placement operation; Figure 4; Placement of tag points on an open complex surface; Figure 5; Recursive numercial algorithm for open surfaces; Figure 6; Tag point distribution on an open complex surface; Figure 7; Tow placement variables for a simple constant cylinder; Figure 8; Tag point distribution on a closed surface; Figure 9; Tow placement simulation on an axis-symmetrical part; (see equation 1); (see equation 2); (see equation 3); (see equation 4); (see equation 5); (see equation 6); (see equation 7); (see equation 8)

DETAILS

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